Name: ________________________________ Class: __________ Date: _____________

**Sec 4 Physics (SSMT / IP)**

Topic 20: Practical Electricity

| *I can…* | *By the end of this topic, you should be able to:* |
|---|---|
| ☐ | describe the use of the heating effect of electricity in appliances such as kettles, ovens and heaters |
| ☐ | recall the relationships P = VI, E = VIt |
| ☐ | apply the relationships for electrical power and energy to new situations or to solve related problems |
| ☐ | calculate the cost of using electrical appliances where energy unit is the kW h |
| ☐ | compare the use non-renewable and renewable energy sources such as fossil fuels, nuclear energy, solar energy, wind energy and hydroelectric generation to generate electricity in terms of energy conversion efficiency, cost per kW h produced and environmental impact |
| ☐ | state the hazards of<br>(i) damaged insulation<br>(ii) overheating of cables<br>(iii) damp conditions |
| ☐ | explain the use of fuses and circuit breakers in electrical circuits and of fuse ratings |
| ☐ | explain the need for earthing metal cases and for double insulation |
| ☐ | state the meaning of the terms: live, neutral and earth |
| ☐ | describe how to wire a mains plug |
| ☐ | explain why switches (placed after fuses), fuses and circuit breakers are wired into the live conductor |

## 20.1 JOULE HEATING

We all know that when an electric current flows in through a resistor, some thermal energy is given out. A common would be the filament shown on the right. When a current flows in the high resistance element, the electrons collide frequently with the ions of the element. Such collisions increase the average kinetic energy of the ions in the filament and give rise to a heating effect. This effect is called **Joule heating**, also known as ohmic heating or resistive heating.

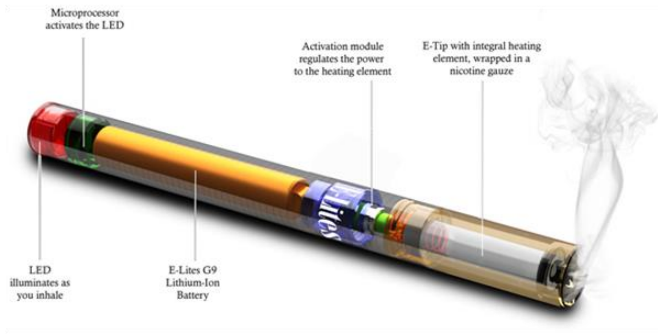
**Check your understanding**

(a) The passage above mentioned a "high resistance element", how high a resistance should it be? Will it work with insulators?

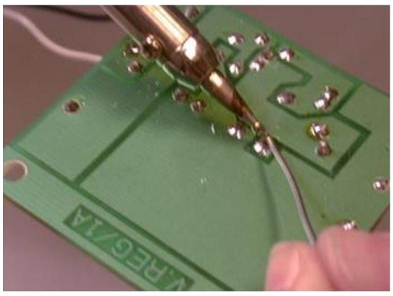
(b) Name some other uses for Joule heating.

Examples of Joules heating

Electric stove




Electric cigarette



Electric solder

Electric fuse

Instant heater

## 20.2 Equations for Joule heating

In this section, we are going to derive a few equations that can guide us in solving problems related to electrical energy. Let's take $V$ as the potential difference across the heating element, $I$ as the current flowing through it, and $R$ as the resistance of the heating element.

Derive the equations $P = VI$, $P = I^2R$ and $P = \frac{V^2}{R}$ using the fact that $Power = \frac{Work}{time}$ and $W = qV$.

$$P = \frac{W}{t}$$
$$= \frac{Vq}{t}$$

Since $I = \frac{q}{t}$, $P = IV$

And $V = IR$, $P = I^2R$

And $I = \frac{V}{R}$, $P = \frac{V^2}{R}$

**Table of equations for Joule Heating**

| Power | Energy |
|---|---|
| $P = IV$ | $W = IVt$ |
| $P = I^2R$ | $W = I^2Rt$ |
| $P = \dfrac{V^2}{R}$ | $W = \dfrac{V^2t}{R}$ |

In solving physics problems related to Joule heating, it is not uncommon to relate it to other forms of energy such as kinetic energy $\left(KE = \frac{1}{2}mv^2\right)$, potential energy $(GPE = mgh)$, thermal energies $(Q = mc\Delta\theta)$, $(Q = ml_v)$, or $(Q = ml_f)$ and so on. Remember that energy can change from one form to another (though not indiscriminately).

**Check your understanding**

(c) A toaster is designed to operate with a voltage of 120 V, and a clothes dryer is designed to operate at 240 V. Based solely on this information, which appliance uses more power?

(d) When an incandescent light bulb is turned on, a constant voltage is applied across the tungsten filament, when then becomes white hot. The temperature coefficient of resistivity for tungsten is a positive number. What happens to the power delivered to the bulb as the filament heats up?

(e) Calculate the resistance of a 40-W automobile headlight designed for 12 V.


$$R = \frac{V^2}{P} = \frac{(12)^2}{40} = 3.6\Omega$$

(f) Lightning bolt is a spectacular example of electric current in a natural phenomenon. There is much variability to lightning bolts, but a typical event might transfer $10^9$ J of energy across a potential difference of $5\times10^7$ V during a time interval of about 0.2 s. Use this information to estimate,

(i) the total amount of charge transferred between the cloud and ground;
(ii) the current in the lightning bolt;
(iii) the average power delivered over the 0.2 s.

(i) $q = \dfrac{W}{V} = \dfrac{10^9}{5\times10^7} = 20$ C

(ii) $I = \dfrac{q}{t} \approx \dfrac{20}{0.2} = 100$ A

(iii) $P = \dfrac{energy}{time} = \dfrac{10^9}{0.2} = 5\times10^9$ W

### 20.3 A new unit kWh

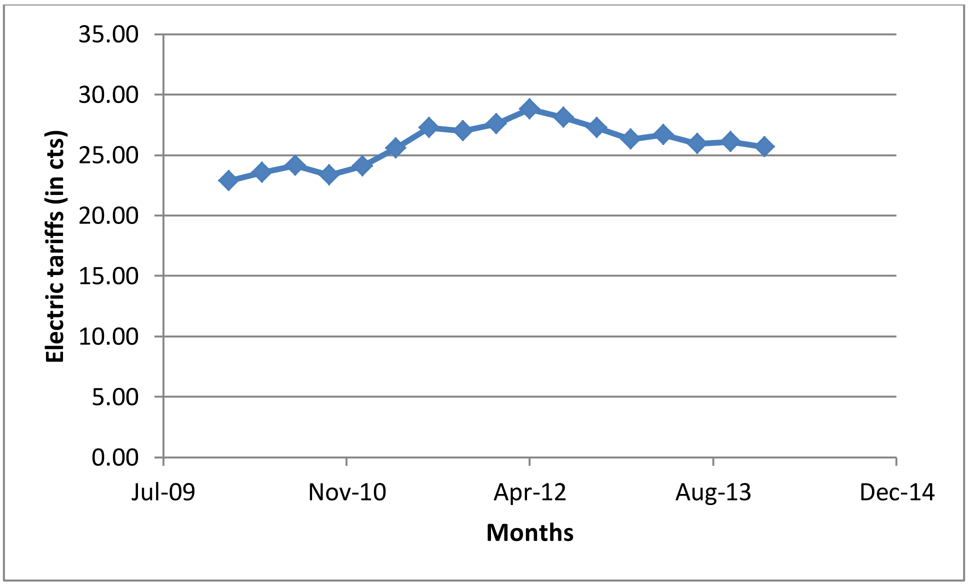
In this section, we shall discuss a new unit of energy called *kilowatt hour*, or kWh. This physical unit is used by electric companies to charge users of electricity.

How many J are there in 1 kWh?

$$1\text{ kWh} = 1(1000)\left(1\ \frac{\text{J}}{\text{s}}\right)(3600\text{ s})$$
$$= 3.6\times10^{6}\text{ J}$$

Below is a sample domestic electric and water bill. You should note that the price of electricity varies according to its usage, whether it is domestic, non-domestic, high tension, extra high tension etc.

| *CURRENT MONTH CHARGES* | *Usage* | *Rate ($)* | *Amount ($)* | *Total ($)* |
|---|---|---|---|---|
| *Electricity Services* | | | | |
| Reading taken on 11-03-2011 : 20946 | | | | |
| Electricity | 220 kWh | 0.2410 | 53.02 | **53.02** |
| *Gas Services by City Gas Pte Ltd* | | | | |
| Reading taken on 11-03-2011 : 6629 | | | | |
| Gas | 73 kWh | 0.1799 | 13.14 | **13.14** |
| *Water Services by Public Utilities Board* | | | | |
| Reading taken on 11-03-2011 : 1612.5 | | | | |
| Water | 17.1 Cu M | 1.1700 | 20.01 | |
| Waterborne Fee | 17.1 Cu M | 0.2803 | 4.79 | |
| Sanitary Appliance Fee | 2 Fittings | 2.8037 | 5.61 | **30.41** |
| *Refuse Removal by SembWaste Pte Ltd* | | | | |
| Refuse | 1 Qty | 5.43 | 5.43 | **5.43** |
| *Water Conservation Tax* | $20.01 | 30% | 6.01 | **6.01** |
| *Total Charges* | | | 108.01 | **108.01** |
| *Goods & Services Tax* | $108.01 | 7% | 7.56 | **7.56** |
| Total Current Charges Inclusive of GST | | | | **$115.57** |




In Singapore, the price of electricity is reviewed every quarter of a year. The price of electricity for 1 Jan to 31 Mar is 25.65 cents per kWh.

**Example 1**

Air conditioners are one of the most energy consuming devices a normal person can use. Consider a typical Mitsubishi Electric Starmex System 3 inverter, at full load, it consumes 2.18 kWh per hour. How much would it cost a family which uses this aircon at full load for 6 hours per day for a period of 30 days? Use the latest available electric tariff of Singapore to solve the problem.


Solution:

$$\text{Price} = (2.18)(6)(30)(0.2565)$$
$$= \$100.65$$

Clearly, we cannot apply the normal rule for significant figures here because the electric company will not follow physics.

**Example 2**

Find the electrical energy stored in the iPhone battery given 3.7 V and 1400 mAh.

$$Energy = VIt$$
$$= 3.7 \times 1400 \times 10^{-3} \times 3600$$
$$= 19 \text{ kJ}$$


*Fossil fuels vs renewable sources of energy*
*(We had a more detailed discussion in the topic of energy, Sec 3)*

"Continued research has made renewable energy more affordable today than 25 years ago. The cost of wind energy has declined from 40 cents per kilowatt-hour to less than 5 cents. The cost of electricity from the sun, through photovoltaics (literally meaning "light-electricity") has dropped from more than $1/kilowatt-hour in 1980 to nearly 20cents/kilowatt-hour today. And ethanol fuel costs have plummeted from $4 per gallon in the early 1980s to $1.20 today.

But there are also drawbacks to renewable energy development.

For example, solar thermal energy involving the collection of solar rays through collectors (often times huge mirrors) needs large tracts of land as a collection site. This impacts the natural habitat, meaning the plants and animals that live there. The environment is also impacted when the buildings, roads, transmission lines and transformers are built. The fluid most often used with solar thermal electric generation is very toxic and spills can happen.

Solar or PV cells use the same technologies as the production of silicon chips for computers. The manufacturing process uses toxic chemicals. Toxic chemicals are also used in making batteries to store solar electricity through the night and on cloudy days. Manufacturing this equipment has environmental impacts.

Also, even if we wanted to switch to solar energy right away, we still have a big problem. All the solar production facilities in the entire world only make enough solar cells to produce about 350 megawatts, about enough for a city of 300,000 people. That's a drop in the bucket compared to our needs. California alone needs about 55,000 megawatts of electricity on a sunny, hot summer day. And the cost of producing that much electricity would be about four times more expensive than a regular natural gas-fired power plant. "

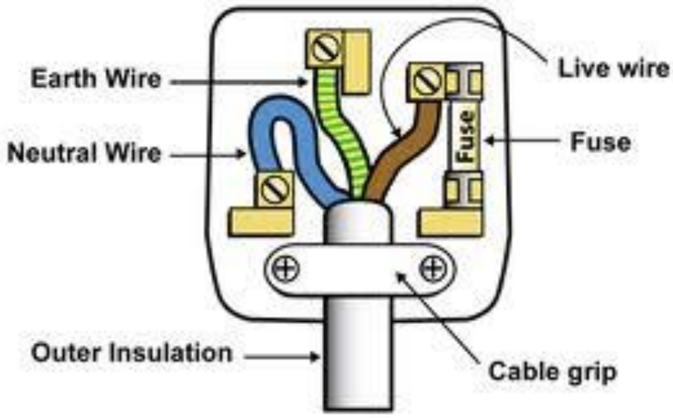
http://www.energyquest.ca.gov/story/chapter17.html
Article is probably written in 2012

**Table for energy sources and their possible environmental impact**

| **Energy Sources** | **Possible Environmental Impact** |
|---|---|
| Biofuels (biomass/biodiesel/ethanol) | Greenhouse gases. |
| Geothermal | Little greenhouse gases |
| Hydropower | Reduce dissolved oxygen levels in water bodies, flow of water bodies. |
| Petroleum | Spills, runoffs, greenhouse gases. |
| Solar | Toxic by-products in production of photovoltaic cells. Water requirement. |
| Uranium | Nuclear waste, heavy metals in water, water pollution. |
| Wind | Bird mortality. |

## 20.4 LIVE, NEUTRAL AND EARTH WIRE

In Singapore, we use the three-pin plug system which contains the live, neutral and earth wire. See picture below.



The live wire is connected to the high potential, in Singapore's case, 240 V. The neutral wire is at 0 V. This is similar to the concept of batteries where one terminal is of higher potential than the other. For safety purpose, the fuse is always connected to the live wire. Can you think of the reason why?

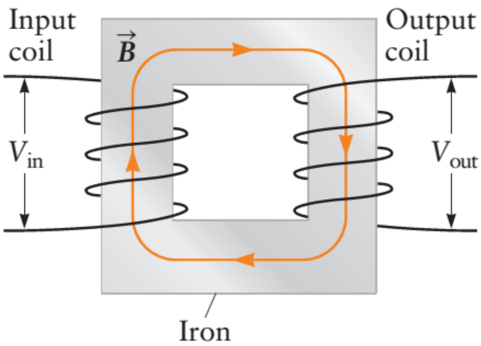
**Live wire**: Connected to the power station (or substation). (brown / black colour)

**Neutral wire**: Connected to power station and earth (or substation). (blue colour)

**Earth wire**: Connected to earth, usually connecting the metal casing of an appliance to earth. (green and yellow strip)

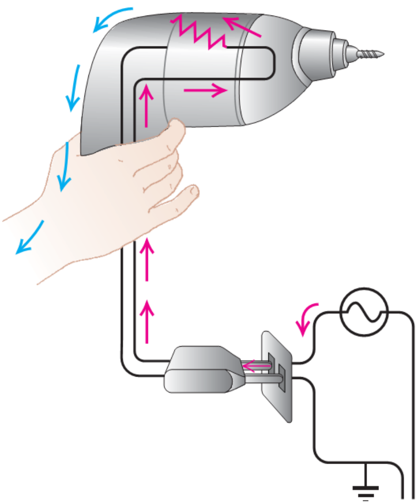
Earth wire

The system of power delivery is not a single current that flows from the power station into our homes. Instead the power cables from the power station is fed into a substation where the voltage is "step-down" for domestic use. This requires the use of a transformer (a device that can alter the voltage of alternating current). We will discuss the use of transformer in greater detail in the topic of electromagnetism.

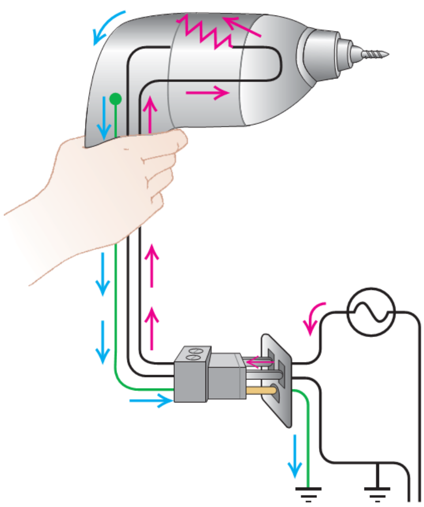



Schematic of a transformer. You can see that the primary input which is coming from the power station is not directly connected to the output coil which delivers electricity to the house. The letter B inside the iron structure is the magnetic field.

With this, we can now make sense of the electrical wiring. Observe the picture below.



two-pin system



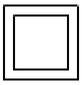
three-pin system

In the normal working condition, the current should be drawn from the live wire through the resistor and exit via the neutral wire. However, should there be a fault with the two-pin system, such as the current is now leaked through the metal casing, a person who touch the electric drill will get a shock.

With the three-pin system, an earth wire is attached to the metal casing of the electric drill. When a fault occurs and current is leaking, the current will prefer to take the path of least resistance and in this case, the earth wire. The user is protected from being shocked electrically.

**Double Insulation**


Some appliances, such as electric drills (left), do not have an earth wire. This is because they have plastic casings, or they have been designed so that the live wire can not touch the casing. As a result, the casing cannot give an electric shock, even if the wires inside become loose. These appliances have double insulation and carry a symbol.

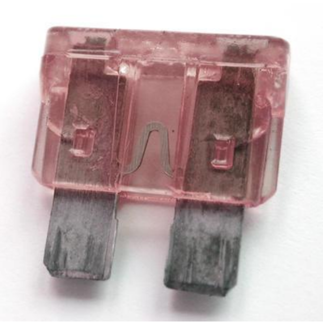


Symbol for double insulation.

### 20.5 SAFETY FEATURES: FUSES AND CIRCUIT BREAKERS

Safety features are a necessary part of domestic electricity. In all electrical appliances, there will be at least one fuse in the system (most often found at the three-pin power plug). A fuse consists of a fine wire manufactured to carry a certain maximum current. Should the current exceed the limit, Joule heating will become hot enough to melt the fuse, thus breaking the circuit.

In electronics and electrical engineering, a fuse is a type of low resistance resistor that acts as a sacrificial device to provide overcurrent protection, of either the load or source circuit. - Wikipedia



car fuse

ceramic fuse

electric fuse

In Singapore, different kinds of fuses are used with different types of plugs. Look at the types of approved mains plugs.

2.5 A round pin

5 A round pin

13 A rectangular pin

15 A round pin

One great advantage of fuses over circuit breakers is that they are very much cheaper than circuit breakers. If we are considering the number of appliances and electrical connections in a typical building, the savings by using fuses can be in the tens to hundreds of thousands.

**2.5 A round pin**: Does not have an earth wire. Usually used in radio, or DVD players where casing is not metallic in nature.

**5 A round pin**: Usually used in table or standing lamps. Often used in hotels. Rarely used in residential area.

**13 A rectangular pin**: Most common of the electric plugs.

**15 A rectangular pin**: Mostly used in air conditioner power supply.

### Circuit Breakers

In HDB Singapore, this is known as the **residual-current circuit breaker** (**RCCB**). In USA, this is known as the **Ground Fault Circuit Interrupter** (**GFCI**). The RCCB is an electrical wiring device that disconnects a circuit whenever it detects that the electric current is not balanced between the energized conductor and the return neutral conductor. Such an imbalance may indicate current leakage through the body of a person who is grounded and accidentally touching the energized part of the circuit. A lethal shock can result from these conditions. RCCBs are designed to disconnect quickly enough to prevent injury caused by such shocks.

RCCBs are designed to disconnect the circuit if there is a leakage current. By detecting small leakage currents (typically 5–30 milliamperes) and disconnecting quickly enough (<30 ms), they may prevent electrocution.

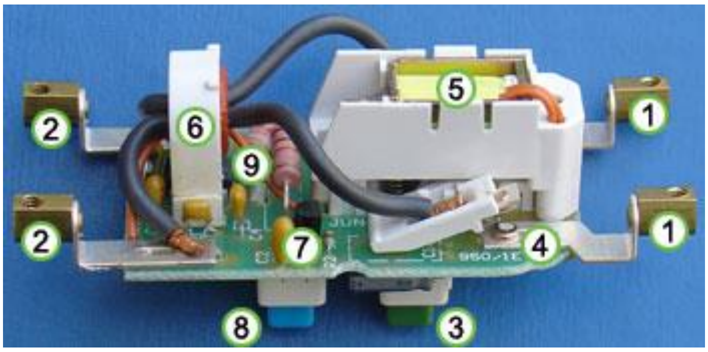
They are not intended to provide protection against overcurrent (overload) or all short-circuit conditions.


RCCB

A distribution box containing many circuit breakers

Extra information

1. incoming terminals
2. outgoing terminals
3. reset button
4. contact
5. solenoid
6. sense coil
7. sense circuitry
8. test button
9. test wire




The incoming supply and the neutral conductors are connected to the terminals at (1) and the outgoing load conductors are connected to the terminals at (2). The earth conductor (not shown) is connected through from supply to load uninterrupted.

When the reset button (3) is pressed the contacts ((4) and hidden behind (5)) close, allowing current to pass. The solenoid (5) keeps the contacts closed when the reset button is released.

The sense coil (6) is a differential current transformer which surrounds (but is not electrically connected to) the live and neutral conductors. In normal operation, all the current down the live conductor returns up the neutral conductor. The currents in the two conductors are therefore equal and opposite and cancel each other out.

Any fault to earth (for example caused by a person touching a live component in the attached appliance) causes some of the current to take a different return path which means there is an imbalance (difference) in the current in the two conductors (single phase case), or, more generally, a nonzero sum of currents from among various conductors (for example, three phase conductors and one neutral conductor).

This difference causes a current in the sense coil (6) which is picked up by the sense circuitry (7). The sense circuitry then removes power from the solenoid (5) and the contacts (4) are forced apart by a spring, cutting off the electricity supply to the appliance.

The device is designed so that the current is interrupted in a fraction of a second, greatly reducing the chances of a dangerous electric shock being received.

The test button (8) allows the correct operation of the device to be verified by passing a small current through the orange test wire (9). This simulates a fault by creating an imbalance in the sense coil. If the RCD does not trip when this button is pressed then the device must be replaced.

## 20.6 ELECTRICAL HAZARDS

<u>Damaged insulation</u>

Live and neutral wires may come into contact with each other, creating a short circuit across the electrical appliance.

Current will increase tremendously in the wire and lead to over-heating resulting in electrical fires.

Exposed wires can also cause electric shocks if touched.

Over-heating

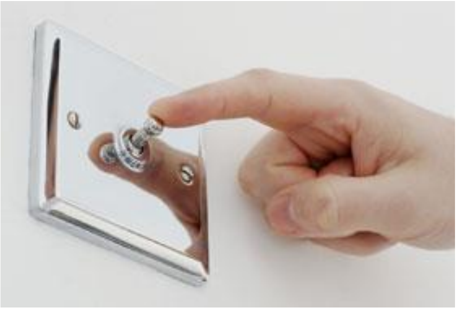
As current flow through wires (especially long wires). Wires are heated up.

Insufficient ventilation will cause the insulation to melt leading to a short circuit.

Damp Conditions

Damp condition creates a parallel circuit across the appliance and decreases the effective resistance of the circuit.

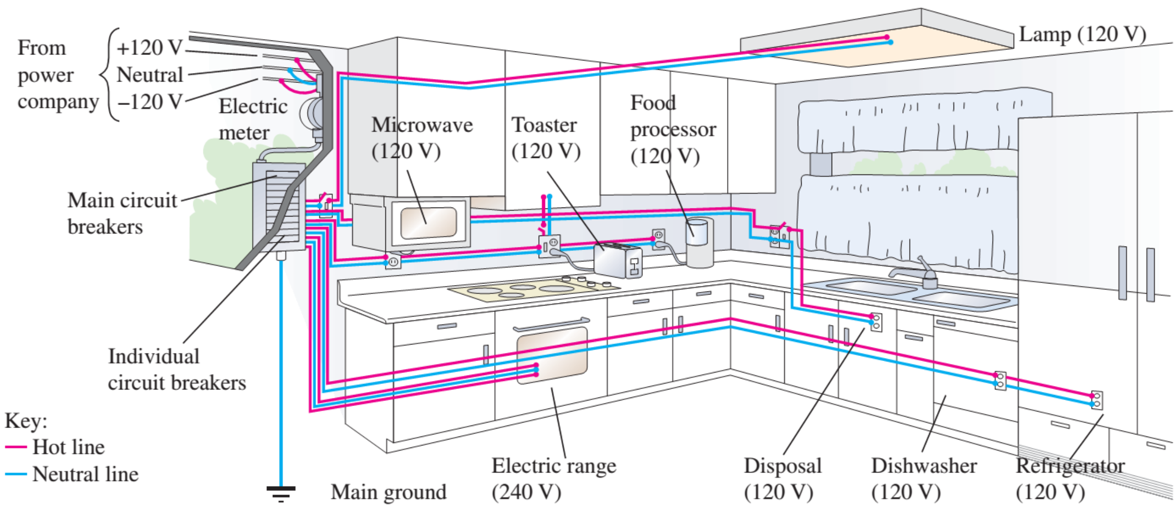
A larger than required current will flow through the cable.



Water is a weak electrolyte and a conductor of electricity.

When using a damp hand to touch a switch, electric current may flow through from the switch to the ground through the body.

Below: A typical kitchen in US (unable to find a good schematic for Singapore)




Schematic diagram of a 120–240 V wiring system for a kitchen. The system includes 120 V circuits on either side of the neutral line, as well as 240 V circuits for high-power appliances such as ranges. Grounding wires are not shown.